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By F. Bollenrath

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By F. Bollenrath

A number of factors are considered which influence the static and fatigue strength of materials under practical operating conditions as contrasted with the relations obtaining under the conditions of the usual testing procedure. Such factors are, for example, interruptions in operation, periodically fluctuating stress limits and mean stresses with periodic succession of several groups and stress states, statistical changes and succession of stress limits and mean stresses, frictional corrosion at junctures, and notch effects. With the aid of a few examples taken from airplane construction, it is shown how the materials testing procedure can take such effects into account as to provide the designer with a useful basis for better utilization of the material. Numerous instructive test results are discussed.

1. INTRODUCTION

In the materials testing procedure for alternating stresses the method of Wöhler is generally followed. A simple test rod is subjected to a periodic alternation of stress between constant stress limits until failure occurs or at least for many millions of stress cycles. From the average dependence of the stress limits on the number of stress cycles up to failure it is concluded that below certain stress limits the number of cycles possible before failure occurs may be arbitrarily large. These test procedures have been very useful in the development of materials with high fatigue strength and are indispensable for the comparison of different materials.

In the application of the materials for technical structures there are many factors, however, which to various degrees affect the strength under alternating stresses

*"Einflüsse auf die Zeit- und Dauerfestigkeit der Werkstoffe." Luftfahrtforschung, vol. 17, no. 10, October 26, 1940, pp. 320-28.

and in materials testing are sometimes not taken into account or only partially. A number of such factors are considered here, as, for example, shape and size of the structural part, character of the surface, machine treatment, temperature, effects of a chemical nature, character of the stress distribution, method of mounting, and stress variation with time.

It would take us beyond the limits of one report to consider in detail the effects of all these factors. A number of operating conditions are considered in detail in testing the material for special application purposes. The report here presented will therefore be limited to the discussion of several factors which have gained in importance because of the present tendency to utilize a structural part up to the limit of its capability and so gain a saving in material, or what amounts to the same thing, in weight. This is in agreement with the modern tendency toward light construction characteristic of the more recent technical developments as the automobile and particularly the airplane. Economy and high performance will in the future lead to an increased tendency in this direction.

2. STRESS UNDER TEST AND OPERATING CONDITIONS

The design of the fatigue strength testing machines generally requires a sine-shape stress alternation between constant limits so that a cosine shape of the loading velocity is obtained. How the Wöhler curve (S-N diagram) is altered when the time-stress curve changes has, as far as the author is aware, received little treatment although in fact - as will be discussed later - deviations from the sine shape very often occur. A limiting case is that represented by fatigue impact tests for studying an impact type stressing, where the effect of the impact velocity has, however, seldom been more closely investigated. Single-stage tests referred to the load limits are carried out up to failure or up to the determination of the fatigue strength.

The Wöhler curve is thus the result of purely single-stage tests. Such stresses occur chiefly in engines and machines which run at the same load for long uninterrupted operating periods and for this range of application the fatigue strength values offer a sufficient basis for the material selection and structural dimensions, taking into account for any individual case a few other varying factors, as scale and shape. This is particularly convenient for many stationary machines which are built for very long life and economy for which the weight considerations do not play a great part and where only low stresses are permitted, to keep down the wear.

Special circumstances may sometimes require that a structural part be subjected to stresses higher than the fatigue strength with a correspondingly shorter life. We are then led to consider the range of limited time strength. The question now arises whether the Wöhler curve still provides a sufficient basis for the dimensioning. It appears necessary for estimating the safety to obtain the curves up to stresses extending beyond those actually intended. Furthermore, it is necessary by means of a larger number of tests to determine the extent of the failure range. There are then obtained the Wöhler curves shown in figure 1 which extend from the static strength to the fatigue strength and limit the failure range.

Complete Wöhler curves are also required, as will be discussed more in detail later, as a basis for strength investigations on the alternating limits of the stress amplitudes under operating conditions. The Wöhler curve shows essentially that a better estimate of safety is obtained from the value of the stress than from the number of stress cycles up to failure. The complete curve will then show that from the static strength up to the start of the steep drop for thousands of stress cycles there corresponds only to a slight decrease in the stress amplitude. The fatigue failures are scattered, however, over a more-or-less wide range, the so-called failure range. Accordingly, only those numbers of cycles can be considered as reliable which are characterized by the lower limiting curve of the failure range.

Where Wöhler curves are available for various lower stress limits complete time and fatigue strength diagrams may be obtained from them (fig. 2). The diagram, shown as an example, refers to heat-treated chrome-molybdenum metal tubes (28 mm outside diameter, 1 mm wall thickness) with a transverse hole of 2 mm diameter at the center of the tube. As a function of the mean stress the upper and lower stress limits are plotted for the fatigue strengths referred to 5×10^6 stress cycles and for the stress limits corresponding to the lower limit of the failure range for

10^6, 10^5, and 10^4 cycles. From such diagrams various kinds of Wöhler curves may be derived which normally are not obtained during the materials testing procedure but nevertheless can be practically useful, as, for example, for constant mean stresses or for constant upper stress limits. The stress range covered by such a diagram is not applied for actual conditions but, corresponding to the various materials, is limited by certain safety factors which may refer to strain limits, rupture strength, or deformations.

Failure itself is the end result of a failure process which extends over many stress cycles where the number of cycles may be very different, depending on the operating conditions. For this reason the number of cycles at the start of failure should be the reference value in estimating the safety. In its initial stages the failure is barely appreciable and no suitable, generally applicable procedure has as yet been developed to detect these initial stages. Experimentally it is known to what extent a series of stress reversals between higher stress limits affects the fatigue strength or the limited time strength between low stress limits. There may be mentioned here the works of H. F. Moore and Wishart, H. F. Moore and I. B. Kommers, H. F. Moore and T. Jasper, I. B. Kommers, H. B. Wishart and S. W. Lyon, H. J. French, Müller-Stock, and others (references 1 to 7). This procedure may be denoted as two-stage tests, a characteristic of which is the continuous succession of load alternations in the single stages, and the higher stage precedes the lower or vice versa.

All numbers of stress cycles which lead to a decrease in the fatigue strength or limited time strength lie on a so-called impairment curve. Whether this kind of curve characterizes the number of load cycles for start of fissure has not yet been conclusively shown. Little has been obtained through comparison investigations as regards the sensitivity of other procedures for determining the start of failure. There may be mentioned here the works of F. Oshiba, who investigated the dependence of notch impact bending strength on the number of load cycles (reference 8). In the methods mentioned, the large number of tests required and the long testing periods are inconvenient factors to be taken into account.

Another method was developed by F. Bollenrath and W. Bungardt (reference 9), who, as shown in figure 3 for constant limits for the deformation amplitude, observed the dependence of the stress amplitudes on the number of load cycles and simultaneously investigated the formation of fissures by the magnetized power process. A lowering in the supporting strength and hence impairment is shown by the stress release which begins earlier the higher the strain amplitudes. Fundametally identical with this process is the determination of the damage from a deformation increasing with the number of load cycles at constant stress amplitudes. Thus, for example, in the bending curves of figure 4 the strong increase in the strain after certain stress cycles indicates a decrease in the supporting strength. Comparison investigations have shown that the degree of the impairment determined by the various methods is not the same. This may be seen directly when it is considered that a different problem is solved by each method: whether the fatigue strength, a definite limited time strength, the notch strength, or the further supporting strength is impaired in the single-stage test. Long before the deflection increases sharply the fatigue and limited times strengths, for example, have already decreased. It is therefore questionable whether for the various investigations the impairment curves can be brought into a definite relation with each other. For this reason the question as to which impairment curve should be used as a basis for the dimensioning of the structural part requires special consideration.

For practically occurring stress conditions the impairment curves of the type described will only rarely be of use. Structural parts which are stressed with a definite number of stress cycles in continuous succession in the range of limited time strength and are then stressed for fatigue strength are few in number. This is not to underestimate the importance of such investigations for the study of the strength properties of materials under alternating stress. All investigations of this type are indispensable for the fundamental study of the problem. At the same time, however, it is useful to study the relations between the results obtained by these investigations and the questions raised by the effective operational stresses. A few of the problems arising will be considered below.

Even when the stress amplitudes remain between the same limits, not all stress reversals follow one another without intermittent rests. This raises the question as to the effect of the intermissions on the limited time and fatigue strengths. This problem may be considered solved mainly by the work of K. Daeves, E. Gerold, and E. H. Schulz (reference 10) on ferritic steels and by the work of the Institute for Materials Investigations of the DVL (reference 11). According to these investigations for soft iron and unalloyed steels with "free ferrite" intermissions in operation appear to permit an increase in the number of cycles up to failure. Otherwise, according to the work of F. Bollenrath and H. Cornelius for alloyed steels and the other materials investigated by them, there is no effect of the intermittent rests on the appearance of the Wöhler curve, as shown by figure 5 for an austenitic steel with 18 percent Cr and 8 percent Ni. For this example all failure load frequencies lie within the failure range for continuously stressed specimens.

In practical operation it is often not the case that equally high amplitudes about a constant mean load are impressed, as in the materials testing procedure. If we consider, for example, the pressure variation in a main connecting rod bearing of a radial engine during one crankshaft rotation (fig. 6), we find a periodic succession of the load with equal frequency between slightly displaced limits and about varying mean loads. The frequency is equal to half the number of rotations since the engine considered is a four-stroke-cycle engine. I should like to show how the actual operational stress deviates from the stress under materials testing conditions and also by another example, namely, the stresses at the root of a propeller mounted on an in-line engine. There will first be shown an extensometer which permits the stress variation at the drive during operation to be measured. Figure 7 shows such a stress recorder mounted on a Hirth crankshaft. The recorder is a very small instrument 10 millimeters long and weighing only 0.5 gram, working on the electrical induction principle, and it was developed at the DVL Institute for Power Plant Mechanics. It is fastened on with cement and can endure a stress of about 1500 grams. With this apparatus, which is unusually sensitive, the stress was measured at the blade root. Figure 8 shows an example of such a record, which was obtained at a rotational speed of 2150 revolutions per minute. It may be seen that we are dealing with a sine-shape stress curve of a frequency equal to half the rotational speed, since the propeller is mounted on a four-stroke cycle engine. By superposing various sine-shape vibrations a type of vibration results from which, to a great approximation, stress fluctuations are obtained which with equal frequency can be arranged within a few displaced stress limits. In the practical investigation of a material for such stresses, equally large stress amplitudes - if the investigation is not carried out on the engine itself - will always be grouped together. The number of equal amplitudes included by a group and the order of succession required of the various groups to approach the stress conditions under practical operation as closely as possible are problems still to be investigated. Some indications are given by investigations such as those of B. F. Körber and M. Hempel (reference 12). Figure 9 shows the results of a few multistage tests on operational stresses. The tests are two-stage in which two groups of bending stress cycles of different magnitude follow each other. It is important to know the number of load cycles each group contains. By subdividing into smaller groups much greater numbers of load cycles above the fatigue strength of 23 kg/mm^2 are supported than in the combination of a large number of load cycles. It is noteworthy in the example given that the groups with stresses of the magnitude of the fatigue strength inserted between the groups with high stress amplitudes can increase considerably the number of stress amplitudes lying in the range of the limited life strength. This phenomenon will be discussed in more detail later.

A type of stressing of the engine-propeller system of airplanes such as that described above occurs only infrequently. For the crankshaft of an airplane engine there are several resonance positions within the practical speed range. The speeds of the resonance range should always be used for as short intervals as possible since the absolutely maximum stresses occur at these speeds. The normal speeds, for example, in cruising are outside the resonance range, so that the greatest number of load cycles lie within considerably lower stress limits. In changing the speed or in starting a few resonance points will, however, always be encountered so that a restricted number of multistage cycles between high limits occur for a large number of load cycles between low limits. In addition, higher stresses may occur in between, as, for example, in starting with full power or in diving flight, and so forth. The design does not take into account an arbitrarily large number of maximum stress cycles in passing through the resonance positions. If an engine is permitted to run continuously at such critical speeds, the crankshaft will perhaps stand up for 10 or 20 hours, at another critical speed perhaps for 50 hours, while at an intermediate speed it may last hundreds of hours or may not fail at all. It follows that the behavior of the material should be investigated for such possible higher stresses that may occur at cruising speeds.

Of a fundamentally different type are the stresses, for example, of the wings of an airplane. This difference is brought out most clearly perhaps by a comparison of a stress record of some part such as the propeller shown above and a part of the airplane wing. Figure 10 shows an acceleration record of an He 70 Lufthansa airplane obtained in straight cruising flight. The accelerations are those due to vertical gusts. The accelerations were recorded with the DVL accelerometer and permit the stresses in the wing to be directly obtained from the record. The average load corresponds to 1 g acceleration. In contrast to the periodic stressing of a part of the engine-propeller system, there is complete absence here of regularity both with respect to the load sequences and load amplitudes and with respect to the mean load at each instant.

A number of extremely important questions arise here with regard to the airplane structure. What should be the dimensioning of the structural parts under such stresses for best utilization of the material and of what significance are the data obtained from the usual materials testing procedure? A final answer to these questions cannot as yet be given. In their discussion it is important to note that for reasons associated with technical development, economy, and intended use, only a restricted useful life of an airplane need be required. Expressed in figures, this means that the airplane must prove itself reliable and safe for only a definite number of operation hours or for a definite total flight distance corresponding to the flight speed.

In what follows, a brief discussion will be given of the method followed in airplane construction to determine the strength of a material or a structural part for withstanding stresses such as those of figure 10. The acceleration records, corresponding to the accuracy of the measurements, are statistically evaluated as regards the frequency with which the acceleration peaks occur within the definite stages (reference 13). The base line is the earth acceleration. Since the accelerations stand in a definite relation to the stresses, statistics are obtained which tell with what frequency certain stress peaks occur within certain stress stages. An example of such a statistical computation is shown in figure 11. Since the unit distribution was found to be approximately symmetrical to the base load, W. Kaul, to set up a rule for load tests combined two equally large, oppositely directed gusts, but not, however, directly following each other in actuality, into one load cycle taking the mean load as that of the undisturbed rectilinear flight. Figure 11, based on the usual Wöhler curve representation for the stress groups 2, 3, and 4, shows the frequency of such load cycles in the stages of the chosen class distribution during 100 hours of operation.

The question to be answered for these cases is what stress value corresponds to a given statistical total frequency. Tests concerned with answering this question may be denoted as statistical strength tests. In discussing these questions I follow essentially the considerations of A. Teichmann and E. Gassner of the DVL Institute for the Strength of Materials. According to figure 12 the operational and entirely arbitrary sequences of load stages may be compared with an ideal sequence. Direct repetitions of equal stages occur only in the lowest stages, monotonically increasing or decreasing sequences only between the lowest and next higher stages. Tests with such an ideal sequence cannot be carried out in view of the millions of cycles required. If equal stages are therefore combined into groups and arranged in monotonic groups, the latter can be sufficiently simplified for practical testing. By taking out one group (that of the third stage, for example) and variously inserting in the remaining sequences the effect of the deviation from the ideal sequence can be determined.

For the carrying out of a practical test A. Teichmann and E. Gassner derive from the flight statistics for a chosen flight range or time a summation curve K_1, which is represented in figure 13 in the usual manner for Wöhler curves. (See reference 14.) In order to shorten the testing time, the continuous summation curve K_1 is replaced by a broken line K_2, which agrees as closely as possible with the curve K_1 and shows with what frequency H a definite load stage is exceeded. The steps to the right and the left of K_2 give the scatter range of the frequencies obtained for several similar tests and approximately equal scatter range of the Wöhler curve. In the test the loads are given in a series of partial summation curves each of which contains the loads for a given operating time, for example, of 250 hours. For an operating time of 3000 flight hours a structural part must safely withstand 12 such partial summation curves.

In what manner should the loads be applied in the test? What is the effect of the series of load cycles between the monotonically increasing and decreasing or alternately increasing and decreasing loads? The effect of increasing load stages can be seen from figure 14, which shows the results from some of the tests of F. Körber and M. Hempel for an unalloyed steel with 0.2 percent C. The alternating stress bending strength is 23 kg/mm^2. Because of the fact that the load cycles first impressed lie between limits below the fatigue strength an understress effect arises, shown by the increase in the fluctuating stress strength by 8.7 to 13 percent. Greater numbers of stress reversals above the fatigue strength are thus possible with increasing load stages. According to investigations of A. Teichmann and E. Gassner on structural parts of steel and duralumin the stress possible for a definite number of load cycles increases in the following order: monotonically decreasing limits, alternating increasing and decreasing limits, monotonically increasing limits. An increase in stress of about 70 percent is thus possible.

Figure 15 shows the results of a statistical strength test. The load cycles lie about the mean load, which is that of the undisturbed rectilinear flight. The start lies at a center stage of the maximum stress values. In the test shown, a partial series includes 0.9×10^6 load cycles. In this case it is required to find the applicable stress for a total number of 10.8×10^6 load cycles, corresponding to 3000 operating hours for a cruising speed of 350 km/h.

In a somewhat more general treatment of the problem the investigation is extended, according to figure 16, to a larger range of operating hours. From a series of tests on duralumin pipes (50 mm diameter and 1 mm thickness) which are notched by 3 holes (5 mm diameter) in the regions of maximum alternating stress, there was obtained the relation shown between the maximum stress peak σ^o and the number of operating hours. The stress σ^v corresponding to the undisturbed stress is in the ratio 1 to 3.4 to the maximum stress σ^o. The test series thus also gives the dependence of the mean stress or the stress in the undisturbed rectilinear flight on the number of operating hours or required life of the aircraft.

Statistical tests have shown furthermore that, according to figure 13, the strength of a test specimen is in no way exhausted if the summation curve K_2 exceeds the impairment curve of French as in this case for the maximum stress value up to 10 kg/mm².

In the tests of the kind described, various other parameters as the load sequence, variable mean load, intermittent rests, and so forth, arising from the operating conditions can be introduced. A discussion of this lies, however, outside the scope of this article.

Through several locally operating conditions a structural part under alternating stress must sometimes be made of larger dimensions than that required by the generally prevailing stresses. Such are individual stress peaks at notch locations and junctures to which in the latter case there is to be added the effect of sliding friction due to differently alternating deformations in the joined parts. In regard to these points I should like to report briefly on some of the test results from the Institute for Materials Testing.

The effect of the surface pressure, considered in detail by O. Föppl and A. Thum (reference 15), was investigated on shafts with transverse holes subjected to alternating torsional stresses. The tests were intended to contribute to the problem to what extent surface pressures at a notch position - in this case, at the transverse hole - contributes to the improvement in the fatigue strength through the cold working or the associated internal stress condition (reference 16). The test specimens were prepared of two light-metal alloys for which, on the basis of previous investigations, the effect of cold working on the fatigue strength was known (reference 17).

In the case of steel the fatigue strength can be greatly increased by cold working, as shown in figure 17, from the tests of H. J. Gough and W. A. Wood (reference 18) for a weakly alloyed steel. Cold rolling of 49 percent increased the fatigue strength by 70 percent. For this reason it is difficult to determine to what extent the cold working contributes to the improvement in the fatigue strength in pressing.

In the case of aluminum-copper-magnesium alloys and aluminum-magnesium puddled alloys, on the other hand, cold rolling up to 60 percent either does not increase the fatigue strength of smooth rods or at the most increases it by 10 percent while in the case of notched rods the treatment even lowers the strength, as shown in figure 18. The shafts, from experiences with transversely bored steel shafts, were pressed at the transverse holes with a pyramid-shape punch with rounded edges.* Figure 19 shows a few of the results of the torsional stresses. The gain in the Wöhler strength is plotted as a percent increase in the torsional strength against the number of load cycles. In the case of material A (Al-Cu-Mg) the improvement is greater than for material B (Al-Mg) but is considerable for both materials. With increasing number of load cycles up to failure the gain decreases and for material B it is practically zero after 20 million cycles.

F. Gisen and R. Glocker (reference 19) found with the aid of X-ray stress measurements on a steel shaft with stamped transverse hole edges that the stresses produced by the pressed edge of the hole change with increasing number of the torsional load cycles. The same was found in the X-ray tests of F. Wever and G. Martin (reference 20) for the changes in internal stresses on specimens of different steels. These investigations indicate that the gain in the Wöhler strength by pressing is to be ascribed more to the arising of internal stress conditions than to the cold treatment working and the elimination of surface faults. According to the investigations of G. Sachs (reference 21) on the fatigue strength of magnesium-alloy propellers there is no tension of the surface pressing at the juncture of the surface. Sachs found, in fact, that the fatigue strength at the juncture was much improved by pressing, although the friction corrosion in the juncture did not appreciably decrease.

The effect of the various factors involved at a juncture, such as kind of material, surface treatment, sliding friction, corrosion, frictional oxidation, and so forth, on the fatigue strength is the subject of numerous papers. (See reference 22.) The phenomena have been explained to a large extent. It still is necessary, however, to determine quantitatively the effect of the individual parameters.

A contribution to this problem will appear shortly in a paper of the Institute for Materials Testing (reference

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*These tests were conducted under the supervision of Prof. A. Thum in the Materials Testing Laboratory of the Technical High School at Darmstadt.

23). A few results of these investigations will be presented briefly. Of particular interest is the problem of the extent to which the stress peaks in the juncture and the friction affect the lowering of the fatigue strength. Considering, for example, the Wöhler curves obtained by W. Müller (reference 24) on rectangular rods of aluminum-copper-magnesium alloy with pressed-on buckles (mean surface pressure, 0.53 kg/mm²) (fig. 20), the impression is obtained that the mounted rods have no fatigue strength. The corresponding Wöhler curve also at higher load cycles shows no tendency to approach a limiting value and is very similar to curves that are obtained for simultaneous corrosion. It is therefore to be supposed that a considerable part of the lowering in the Wöhler strength is to be ascribed to steady frictional corrosion, depending on the number of load cycles.

In the investigation of rectangular rods of a normally annealed, unalloyed steel (St C 35.61) stressed in tension there was found the dependence shown in figure 21 of the frictional oxidation on the surface pressure for 10^6 load cycles. In the juncture the steel St C 35.61 was tested in mutual action with itself (curve a) with a chrome-molybdenum steel tempered to a Brinnel hardness of 400 kg/mm² (curve b) and with sheet brass Ms 67 (curve c). With surface pressure in the juncture the frictional oxidation at first strongly increases and for a surface pressure of about 0.5 kg/mm² attains a maximum value; with increasing surface pressure the frictional oxidation again strongly decreases and at 5 kg/mm² surface pressure becomes inappreciably small. In joining to the heat-treated steel the frictional oxidation is a maximum; for the steel St C 35.61 it is somewhat smaller, and for brass it is only a fourth of that for the heat-treated steel. In figure 22 the tensional strength at the juncture is plotted as a function of the surface pressure at the juncture. It is seen that the fatigue strength in general decreases linearly with the surface pressure. This is to be taken as due to the increasing local stress. Only at low pressures at the juncture is the decrease greater.

According to the relations shown above between frictional oxidation and bearing pressure of the fixing pieces the difference between the linear and actual decrease of the tensional strength is to be ascribed to the frictional oxidation. Since the frictional oxidation and the notch effect and decrease in cross section due to it is a function of the number of load cycles it appears to be of advantage, for similar relations between rod cross section and joining surface, to use a fixation pressure no smaller than 4 kg/mm^2 if the structural part is designed for fatigue strength. In dimensioning for limited time strength it is conceivable that smaller surface pressures are of advantage in spite of the higher frictional oxidation. Investigationsin this direction with further materials are still in progress.

3. SUMMARY

The stresses occurring under actual operating conditions are compared with those corresponding to the conventional test procedure. A distinction is to be made between structural parts which are subject to stresses lying between not widely varying limits or limit groups with a very large number of load cycles and structural parts for which the fluctuation of the stresses occurs between irregularly varying limits with widely varying but restricted frequency corresponding to a prescribed length of life. For the former case the fatigue strength is to be investigated for the stresses arising within the multistage limits and the effect of any succession of limit groups of various frequency. The other case, on the contrary, is to be considered statistically and the safe stress investigated for a given frequency. In discussing these problems consideration is given to the effect of intermittent breaks in operation on the Wöhler strength and to the methods whereby the test procedure can be made to approach the stresses under operating conditions. With the aid of a few examples from airplane construction it is shown how the material can be tested in a statistical sense. With a strength investigation carried out from the point of view described a wider basis may be expected for the proper design of structural parts under actual stresses with a reliable safety estimate and better utilization of the material obtained. Finally some results are given of a few investigations on fatigue strength in mountings and the effect of surface pressures on the limited time and fatigue strengths.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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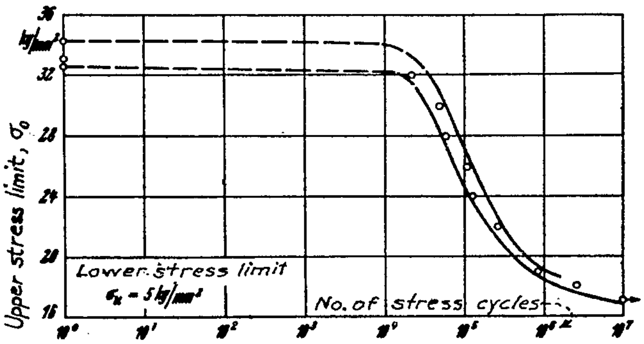


Figure 1.- Wöhler curve for an aluminum alloy with 6 percent Mg and 1 percent Zn.

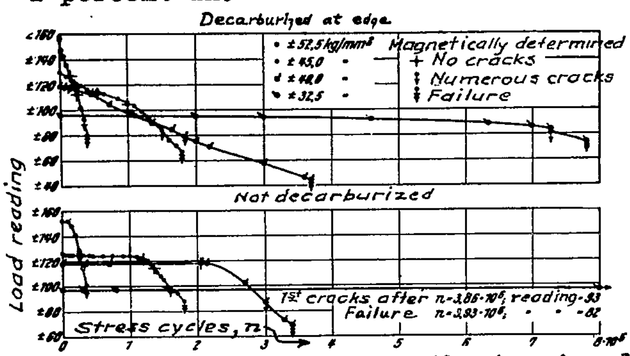


Figure 3.- Dependence of the torsional stress limits on the number of load cycles for tension wires for various strain limits.

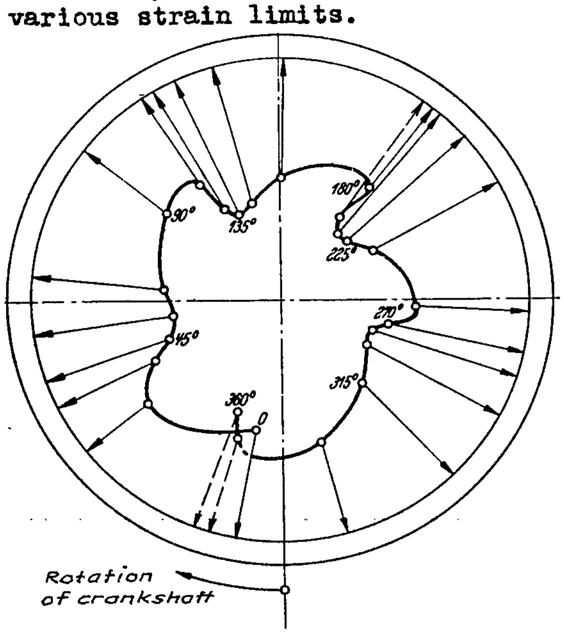


Figure 6.- Variation of the pressure in magnitude and direction in bearing of a radial engine during one crankshaft rotation.

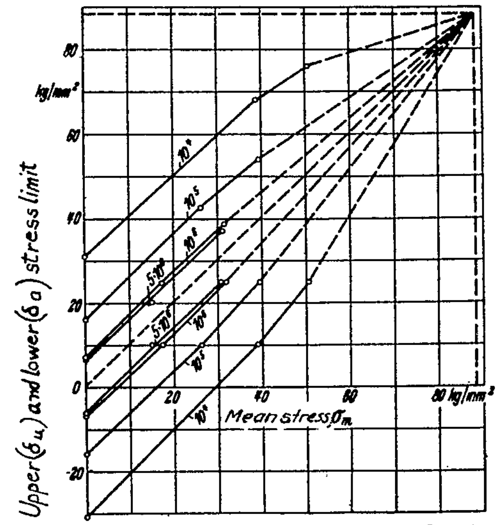


Figure 2.- Limited time and fatigue strength diagram for heat treated chrome-molybdenum steel tubes, aviatiom material 1452, with a transverse hole of 2 mm diameter.

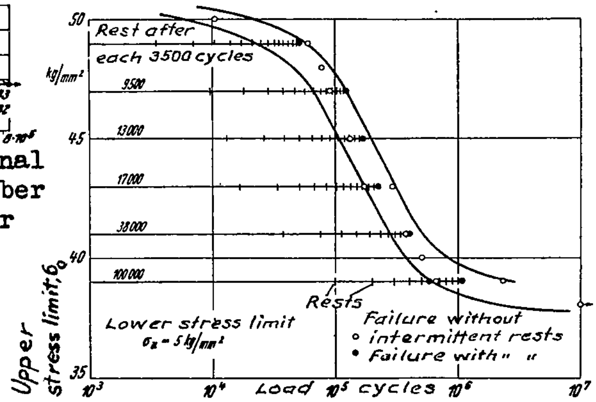


Figure 5.- Effect of intermittent rests on the Wöhler strength of an austenitic chrome-nickel steel (18 percent Cr, 8 percent Ni).

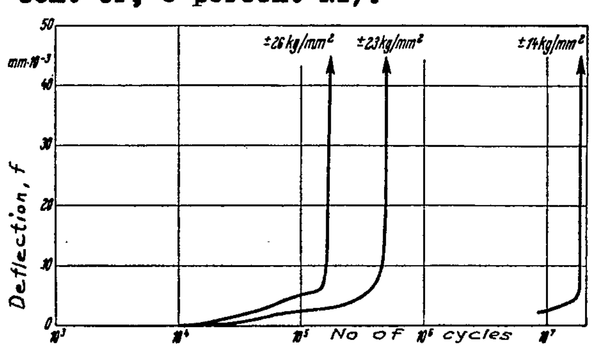


Figure 4.- Dependence of the flexural strain on the number of load cycles for duralumin.

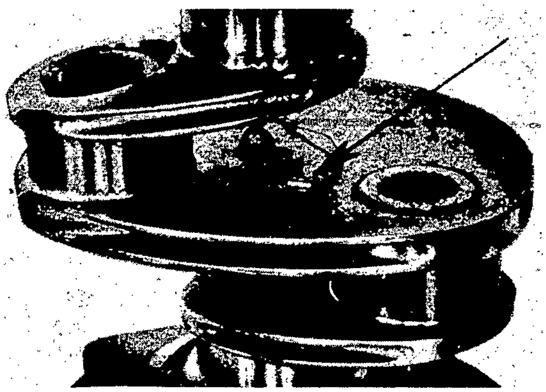


Figure 7.- Electrical (induction) extensometer of the Institute for Power Plant Mechanics of the DVL.

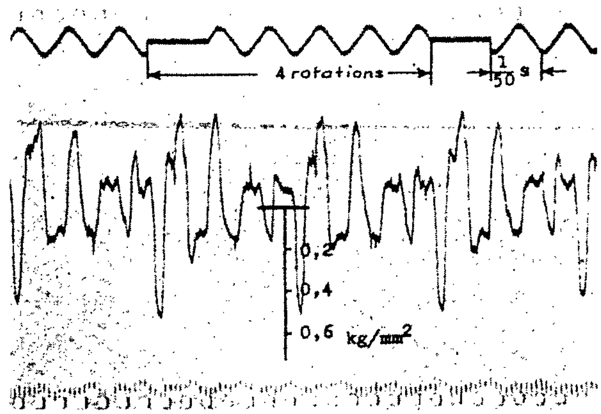


Figure 8.- Record of stress at a propeller blade root, measured with the instrument shown in fig. 7. (BMW 132 engine, n=2150 rpm).

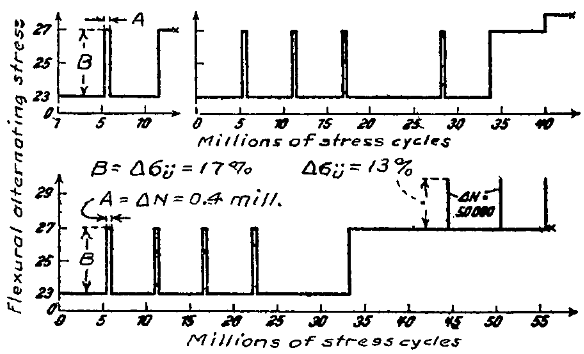


Figure 9.- Variation in the flexural fatigue strength of an unalloyed annealed steel with 0.2 percent C in overloading (F. Körber).

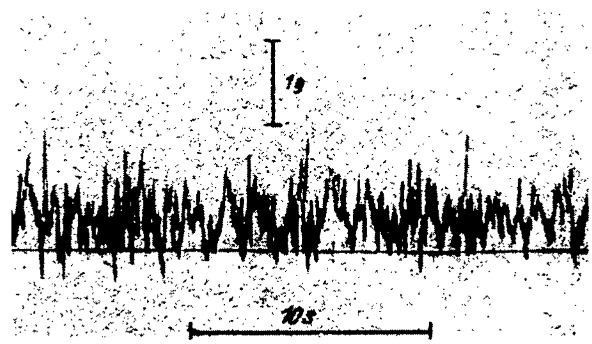


Figure 10.- Acceleration due to vertical gusts of an airplane in cruising (He 70, UDAS).

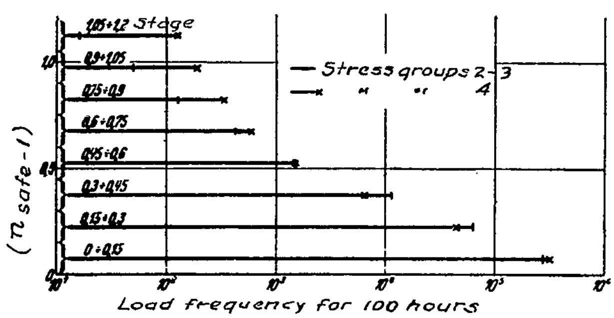


Figure 11.- Frequency of the loads in multiples of (n_{safe}-1) for 100 operating hours (computed for a flight velocity of 350 km/h); (n_{safe}-1) is the safe load which due to gusts is added, according to the structural requirements, to the load in the undisturbed and unaccelerated rectilinear flight for airplanes.

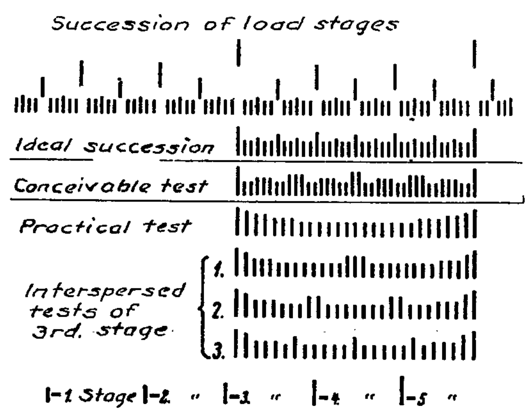
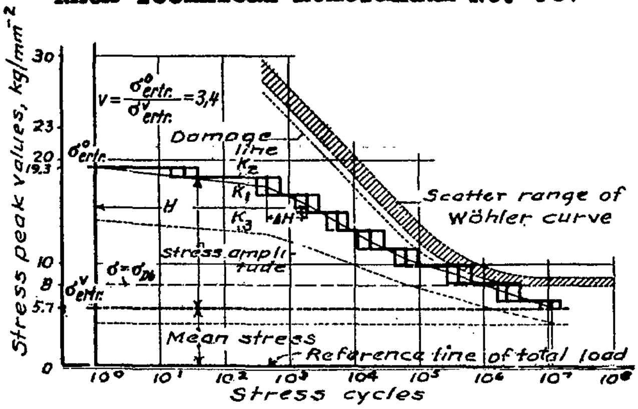


Figure 12.- Sequences of load stages (A. Teichmann).



K_1 given summation curve of the operational loads (see fig. 1)
K_2 summation curve of the test
K_3 admissible summation curve at a safety factor 1.35
H frequency in excess of a given stage of the added gust load in the test
ΔH frequency of attaining a given stage of the added gust load in the test

Figure 13.- Results of a statistical strength test (E. Gassner). Test specimen: Duralumin tube 50•1 (aviation material 3115) with 5 mm hole in the maximum stressed fibers; $\sigma_B = 46$ kg/mm^2, $\sigma_{0.2}$ = 34 kg/mm^2 (admissible minimum values for material σ_B = 40 kg/mm^2, $\sigma_{0.2}$ = 28 kg/mm^2

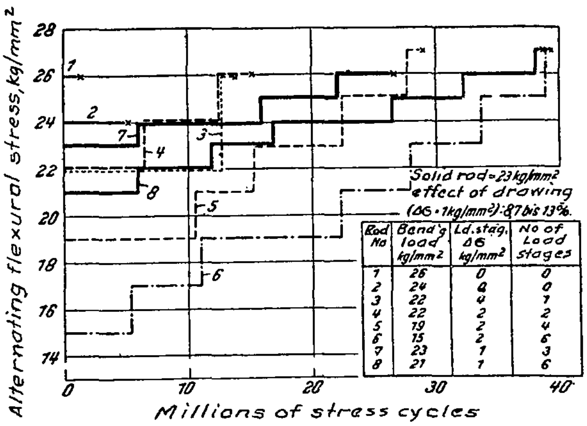


Figure 14.- Variation of the flexural fatigue strength through understress effect, unalloyed steel with 0.2 percent C (F. Körber).

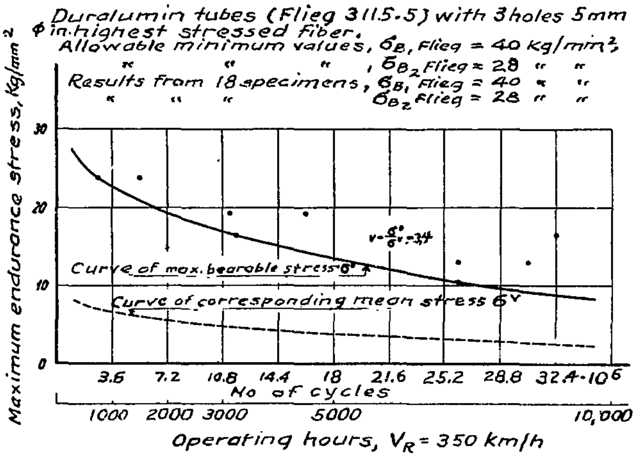


Figure 16.- Stress curve for duralumin tubes with 3 holes (5 mm diam) in the maximum stressed fibers (E. Gassner).

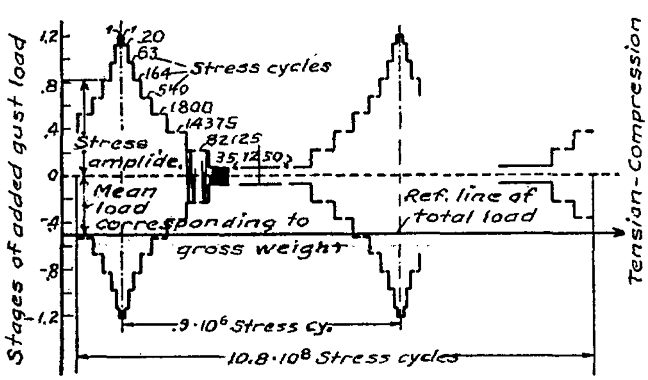


Figure 15.- Statistical strength test results (E. Gassner).

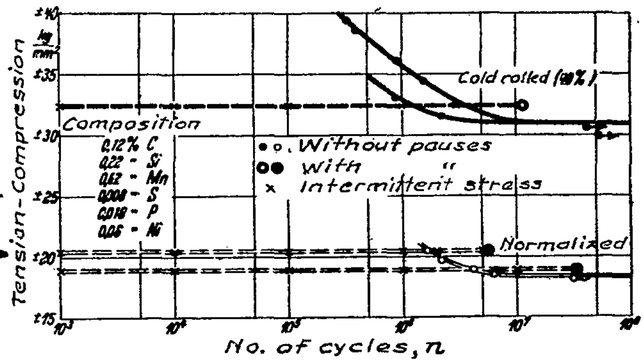


Figure 17.- Effect of cold working and operating breaks on the Wöhler strength of a steel (H.J.Gough and W.A.Wood).

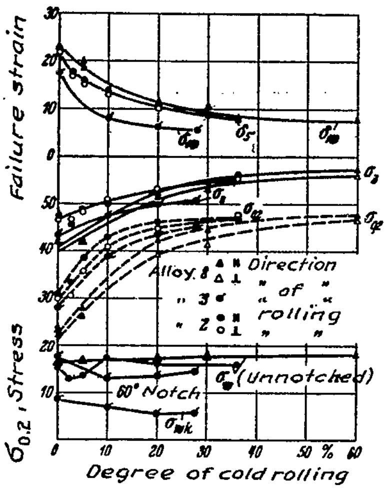


Figure 18.- Dependence of strength properties on the degree of cold rolling for several aluminum alloys.

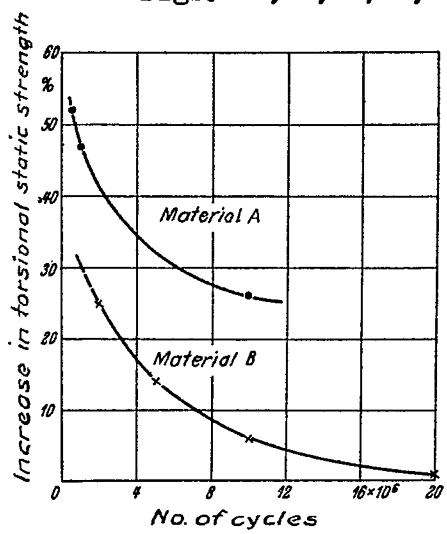


Figure 19.- Effect of pressing the hole edges on the torsional static strength of two aluminum alloy shafts with transverse holes.

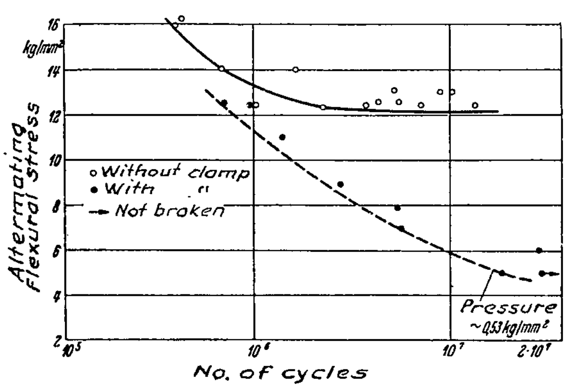


Figure 20.- Effect of end fixation on the Wöhler strength of an aluminum alloy (Al-Cu-Mg) for alternating bending stress (W. Müller).

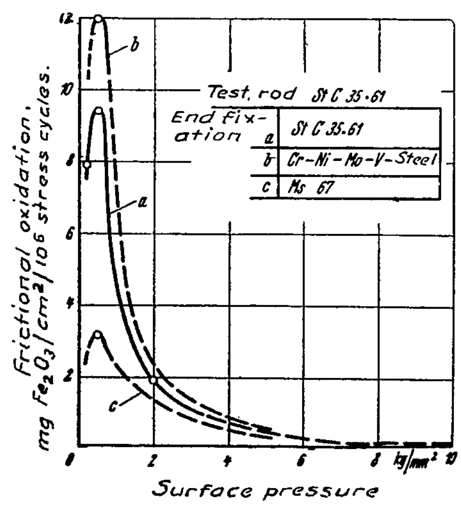


Figure 21.- Frictional oxidation as a function of surface pressure and material saving in the juncture for St C 35·61.

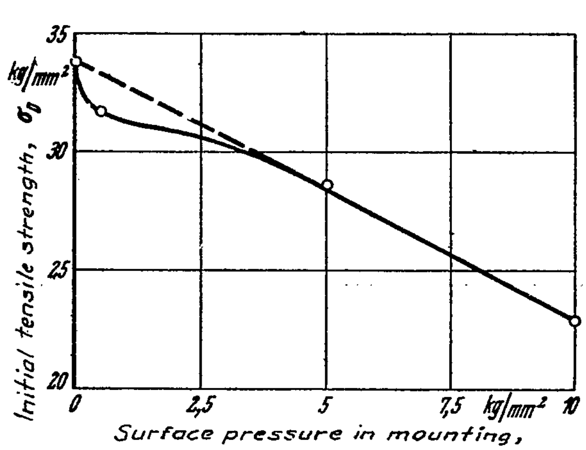


Figure 22.- Tensional trength as a function of the surface pressure in the juncture for St C 35·61.